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None

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UK CL (Edition N) **B3A , H2A AKF2 AKH2**
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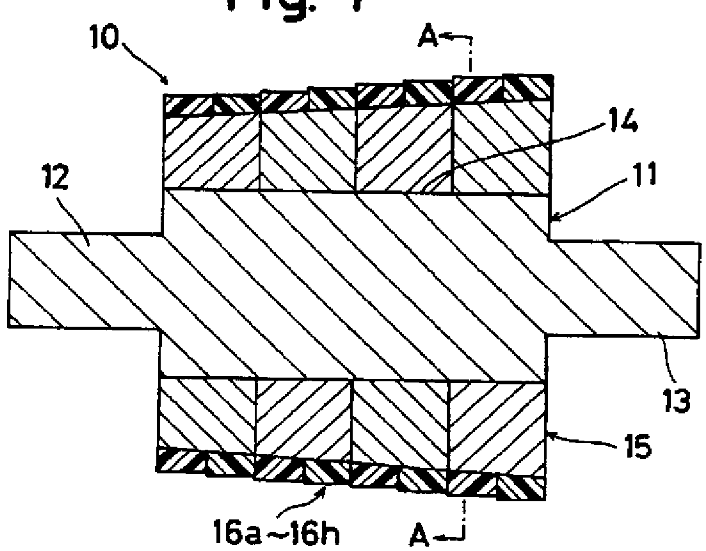
(54) **Method of assembling a permanent magnet rotor**

(57) A method of assembling a permanent magnet rotor includes the steps of:
(a) forming a rotor hub (11); (b) securing segments of permanent magnet (15) on the rotor hub (11) for example with adhesive; (c) machining the segments of permanent magnet (15) so that a continuous shallow taper (α) is formed over the outer diameter of the segments of permanent magnent from one axial end of the rotor hub (11) to the other and (d) axially fitting around the other circumference of the permanent magnet segments (15), from the smaller diameter end thereof, a plurality of retaining rings (16a-16h) made of high strength composite materials and having a decremental change in inside diameter equivalent to the change in magnet outside diameter due to the effect of the taper, the retaining rings (16a-16h) being moved axially to engage the outer circumferential surface of segments of permanent magnet (15) with a predetermined interference.

Fig. 1



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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

Fig. 1

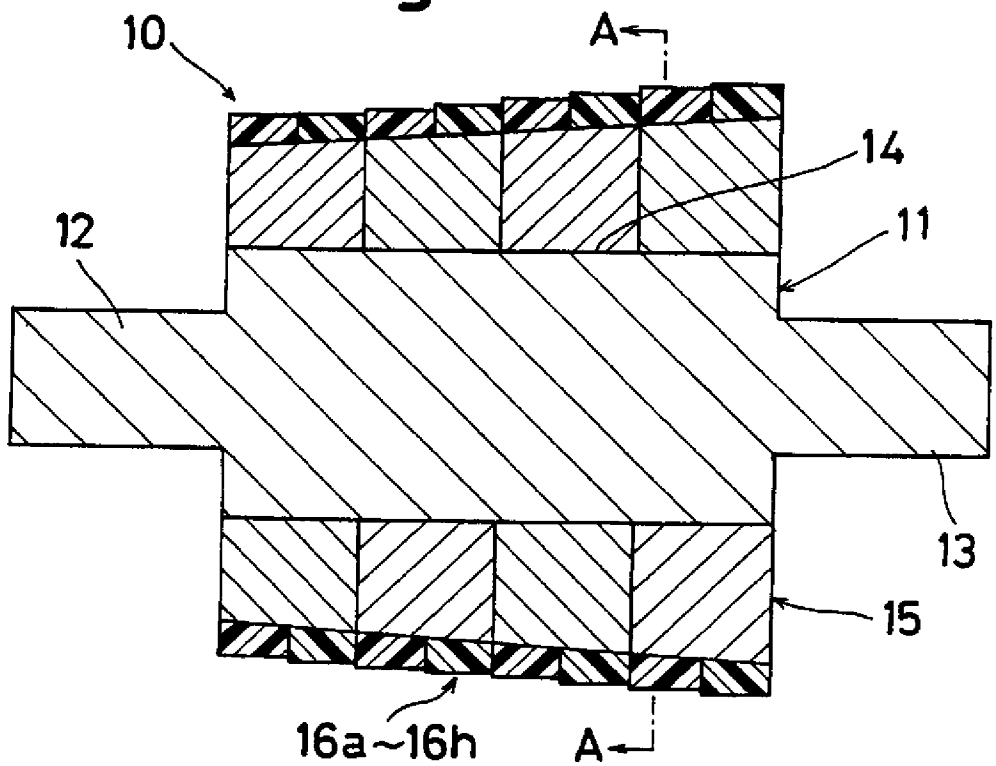


Fig. 2

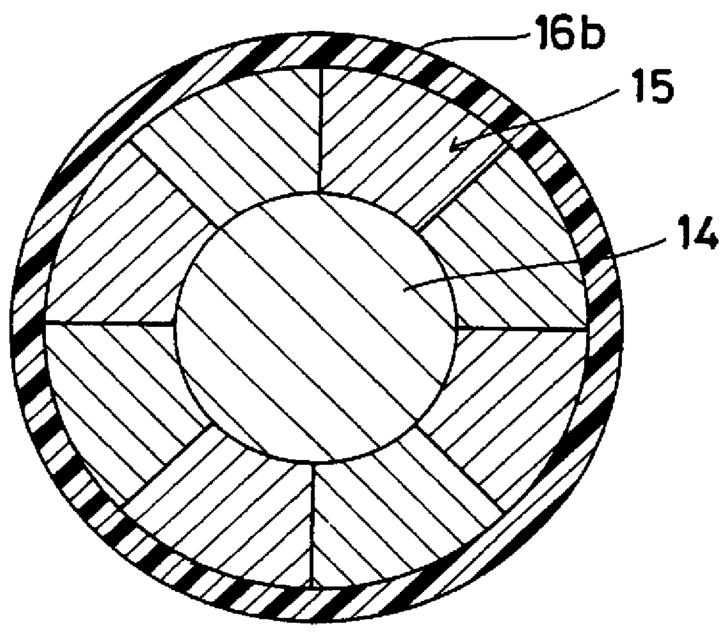


Fig. 3

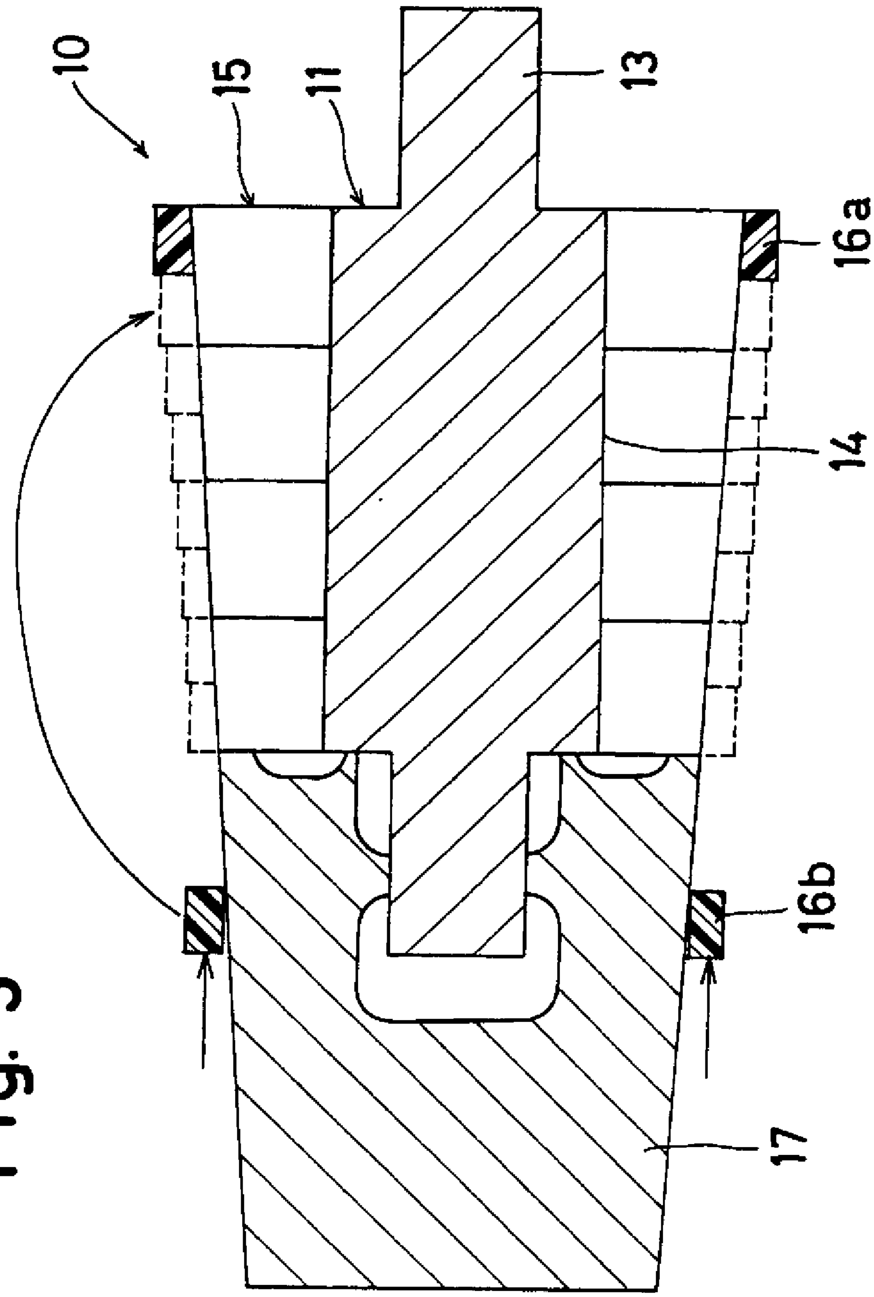


Fig. 4

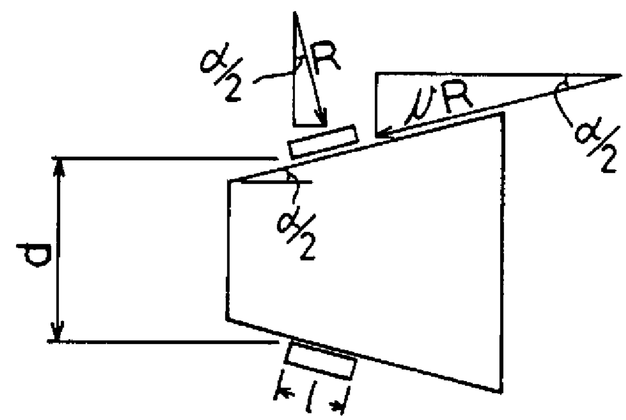


Fig. 5

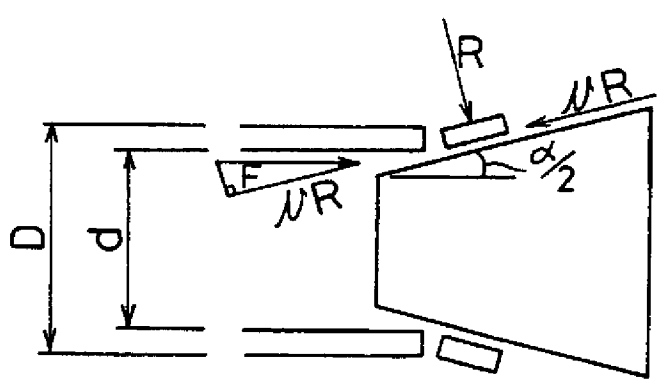
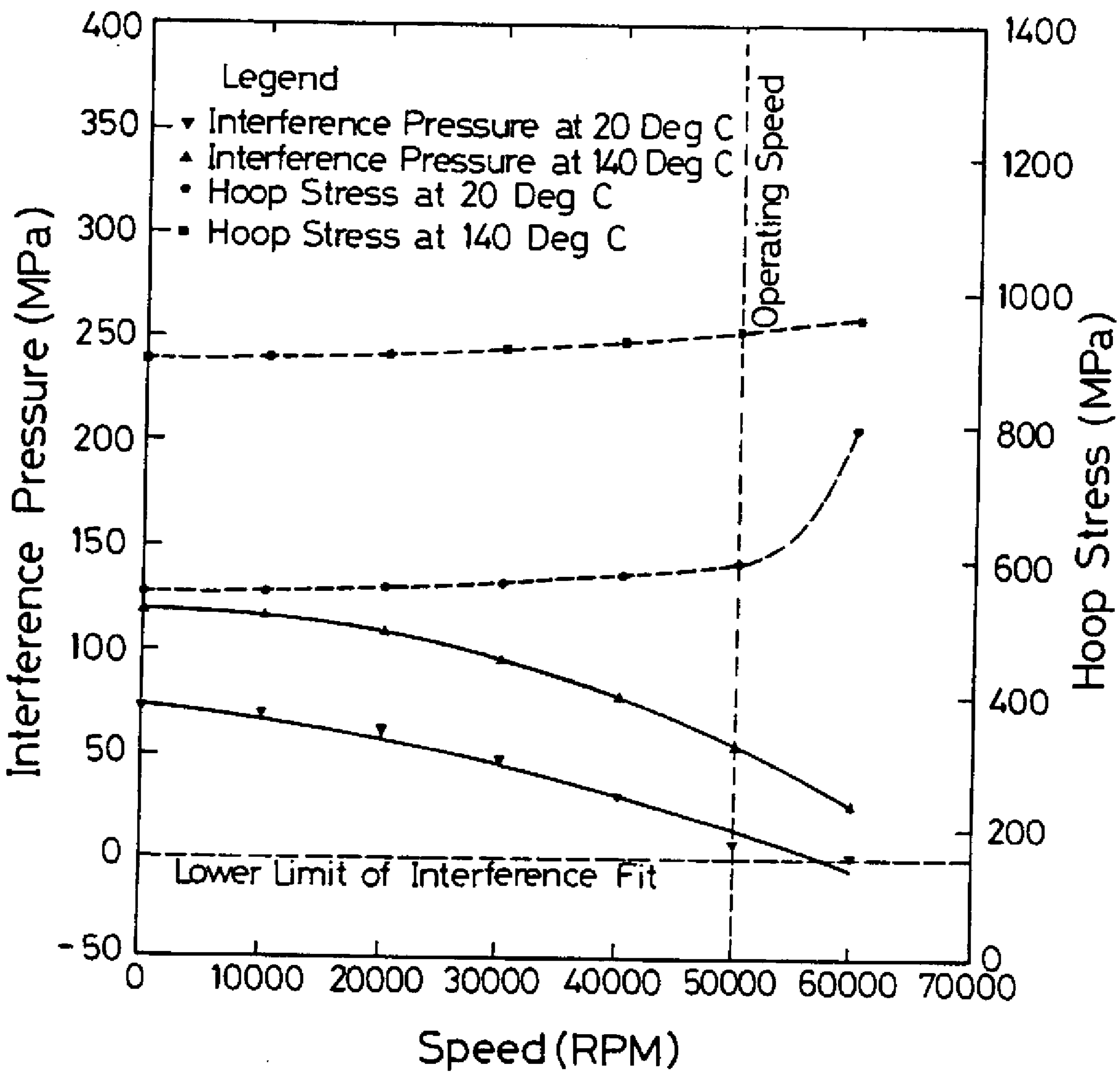


Fig. 6


Legend
Interference Pressure at 20 Deg C
Interference Pressure at 140 Deg C
Hoop Stress at 20 Deg C
Hoop Stress at 140 Deg C
Operating Speed
Lower Limit of Interference Fit
Interference Pressure (MPa)
Hoop Stress (MPa)
Speed (RPM)
400
350
300
250
200
150
100
50
0
-50
1400
1200
1000
800
600
400
200
0
0
10000
20000
30000
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TITLE

Method Of Assembling A Permanent Magnet Rotor

BACKGROUND OF INVENTION

Field of the Invention

The present invention relates to a synchronous permanent magnet machine (motor/generator) having a rotor which has segments of permanent magnet fixed around a shaft, and more particularly to a method of assembling a permanent magnet rotor in which segments of permanent magnet are held using high strength composite materials allowing for rotor peripheral speeds in excess of 200 m/sec.

Description of the prior art:

In conventional synchronous permanent magnet machines, segments of permanent magnet are secured to a shaft by any of a variety of means. Care must be taken to assure that such securement prevents the segments of magnet from moving either axially or radially. If axial movement were permitted, one or more of the magnetic segments on the rotor may not properly align with the armature, with the consequence that machine efficiency would diminish. If any radial movement were to take place, then a dynamic imbalance would be generated, and could cause a bearing or shaft failure or a bad vibration. In the worst case, radial movement of the magnetic segments could prevent high speed rotation of the rotor. Furthermore any interfering contact between the rotor and the stator would cause frictional drag and/or damage to the machine parts.

The reliable securement of magnets increasingly becomes a problem with increased rotor speeds due to the increasing forces tending to cause magnet movement, particularly in the radial direction, with the increasing centrifugal force accompanying increasing rotational speeds. Therefore, it has been proposed in, for example, US-A-4674178 and US-A-3968390 that a retaining can made of high

strength composite materials such as CFRP (carbon fibre reinforced plastic) is fitted onto the magnets in order to restrain the magnets in the radial direction.

Modern CFRP materials have an ultimate tensile strength (UTS) which can exceed 2000 MPa with currently commercially available fibres and resin systems. A high speed permanent magnet motor or generator operating at a peripheral speed in excess of 200 m/sec may require the retaining can to be so tight that 1000 MPa or more tensile stress (σ_t) in the hoop direction (hoop stress) is necessary. The hoop stress can be obtained from equations such as those found in Roak & Young, "Formulas for Stress and Strain" fifth Edition published in 1985 by McGraw-Hill. Anyone skilled in the art of stress analysis can determine the hoop stress in the carbon fibre composite retaining can which is caused by thermal effect, internal pressure caused by centrifugal loading of the magnets, centrifugal body stresses and internal pressure caused by an interference fit. It can easily be determined that rare earth permanent magnets such as Neodymium Iron Boron cause stress of 1000 MPa in a carbon fibre composite can when rotating at a peripheral speed in excess of 200 m/sec.

Given that typical CFRP composite material may have a Young's Modulus E of around 140 GPa then a strain value of $\sigma_t/E = 0.007$ is required in the can. That means that, for a rotor of magnet outside diameter 100mm, the can in its natural unstressed condition before fitting would require an inside diameter 0.7% less at 99.3 mm. In order to fit two components together in the so called shrink fit method as proposed in the above publications, the can must be expanded by heating or the rotor shrunk by cooling. However, carbon fibre has a very small coefficient of expansion and the maximum temperature to which it can be heated is limited by the thermosetting cure termperature

which is normally about a maximum of 180°C. Therefore one must consider shrinking the rotor by cooling. The calculation below, however, shows that cooling the rotor prior to fitting the retaining can is never going to attain the desired initial strain value in the can.

The equation defining the thermal expansion and contraction of a material is :

$$\delta L = \alpha \times L_O \times \Delta T$$

where δL is the change in a linear dimension (in this case the diameter of the rotor);
α is the coefficient of thermal expansion;
L_O is the initial linear dimension (in this case the external diameter of the rotor); and
ΔT is the change in temperature.

If the rotor were to have a coefficient of thermal expansion, α, of about 12 microns per metre per degree Celcius, then the temperature reduction ΔT necessary to cause a 7% reduction in the diameter of the above rotor would be given by:

$$\Delta T = \frac{\delta L}{\alpha \times L_O} = \frac{0.7}{12.10^{-3}} = 584\ °C$$

Room temperature is only about 300°C above Absolute zero so that it is clearly impossible to establish the desired initial strain value in the can by the shrink fit method taught in the above US Patents. It has therefore until now been impossible to establish the above initial strain values for the proper running of high speed permanent magnet motors and generators at peripheral speeds of over 200 m/sec.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a new and improved method of assembling a permanent magnet rotor which overcomes the above drawback.

The invention provides a method of assembling a permanent magnet rotor, comprising the steps of:

(a) forming a rotor hub;

(b) holding segments of permanent magnet on the rotor hub;

(c) machining the segments of permanent magnet so that a continuous shallow angle taper is formed over the outer diameter of the segments of permanent magnet from one axial end of the rotor hub to the other axial end; and

(d) axially fitting around the outer circumference of the permanent magnet segments, from the smaller diameter end thereof, a plurality of retaining rings made of high strength composite materials and having a decremental change in inside diameter equivalent to the change in magnet outside diameter due to the effect of the taper, the retaining rings being axially moved to engage the outer circumferential surface of the segments of permanent magnet with a predetermined interference.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a sectional view of a permanent magnet rotor made according to the present invention;

Fig. 2 is a sectional view taken substantially along the line A-A of Fig. 1;

Fig. 3 is a view similar to Fig 1, but showing the permanent magnet rotor at an intermediate point in its assembly;

Fig. 4 and Fig. 5 are schematic views for explanation of the present invention; and

Fig. 6 is graph of hoop stress and interference pressure versus speed in the carbon fibre ring in the high speed generator.

DESCRIPTION OF THE PREFERRED EMBODIMENT

A method of assembling a permanent magnet rotor in accordance with a preferred embodiment of the invention will be described with reference to attached drawings.

In Fig.1 and Fig. 2 a permanent magnet rotor 10 is provided with a rotor hub 11 which is made of a magnetic material. The rotor hub 11 includes a pair of shaft portions 12, 13 and a central portion 14 which is formed between the shaft portions 12, 13 and which has a larger diameter than that of the shaft 12, 13. Plural segments of permanent magnet 15 made of a rare earth material such as Nd, Sm-Co are secured around the central portion 14 of the rotor hub 11 with an adhesive. The rotor hub 11 may have a central portion 14 of uniform diameter from end to end as shown, or it could have a recess or annular groove between its ends in which the plural segments of permanent magnet are adhered.

As previously explained the forces and stresses required in a modern carbon fibre can, to restrain the segments of permanent magnet in the radial direction, are very large. For very high speed rotors it is no longer possible to use techniques which involve temporarily heating or cooling one component to make the fit possible by thermal differential expansion. Fig. 1 and Fig. 3 show how the segments of permanent magnet 15 are secured in place by a plurality of retaining rings 16a-16h in accordance with the present invention.

The outer circumferential surfaces of the segments of permanent magnet 15 are machined by an accurate method such as grinding so that a progressive shallow taper is formed over the outer diameter of the segments of permanent magnet from one axial end of the central portion 14 to the other axial end. In the embodiment as

illustrated, there are no side plates made of non-magnetic material fixed to the shaft portions 12, 13 in order to restrain the magnets 15 in the axial direction. However, the provision of such side plates is possible according to the invention, in which case the side plates are ground to the same taper as the segments of permanent magnet 15.

Next, on the outer circumferential surface of the segments of permanent magnet 15, a plurality of retaining rings 16a-16h made of high strength composite materials such as carbon fibre and curable epoxy resin are fitted thereon with a predetermined interference. The retaining rings 16a-16h have a decremental change in inside diameter equivalent to the progressive change in magnet outside diameter due to the effect of the taper. This inside diameter can be simply machined or determined by the mandrel upon which each ring is orignally filament wound. The inside diameter of each retaining ring 16a-16h is smaller than the approximate outside diameter of the portion of each corresponding segment of permanent magnet 15 by a predetermined amount. However, each ring could have an inside diameter which has a taper to match that of the magnet outside diameter so long as it is sized to have the predetermined interference.

In this embodiment, the axial length of each of the retaining rings 16a-16h is half of that of each of the segments of permanent magnets 15. Thereby, even though one of the rings 16a-16h might be destroyed in use, since the segment of magnet 15 cannot move in the radial direction, the adjacent ring will be able to prevent axial movement of the magnet segment 15. Therefore, it is desirable that each of the segments of permanent magnet 15 is secured by at least two retaining rings.

The slight taper of the magnetic segments causes a variable spacing between the rotor and the stator from one

end of the rotor to the other, but the variation is very small and has no significantly adverse influence on performance of the motor/generator.

As shown in Fig. 3, the taper of the outside diameter of the segments of permanent magnet 15 provides a slope up which the retaining rings 16a-16h can be pushed. In order to be able to fit all of the retaining rings 16a-16h, a starting tool 17 is provided which is designed to locate accurately with the rotor hub 11 at the axial end where the magnet outside diameter is least. The starting tool 17 has a taper which matches that of the magnet outside diameter.

The interference between each of the retaining rings 16a-16h and each of the segments of permanent magnet 15 is so tight that the segments of permanent magnet 15 do not need to be retained by any other means. The taper angle α can be chosen to suit the application, but it must always be shallow. The taper angle α is limited as follows:
Referring to Fig. 4 the reaction R (in Newtons) is equal to the product of the inside surface area of the ring and the interference pressure, ie

$$R = \pi \times d \times l \times P$$

where d is the mean internal diameter of the ring;
l is the axial length of the ring; and
P is the interference pressure

The force F (in Newtons) required to overcome friction is given by:

$$F = \mu \times R = \mu \times \pi \times d \times l \times P$$

where μ is the coefficient of friction

If α is the included taper angle then the maximum value of α to ensure adhesion of the ring is given by:

$$\mu \, R\cos(\alpha/2) > R\sin(\alpha/2)$$

$$\mu > \tan(\alpha/2)$$

Furthermore, the frictional resistance caused by the interference pressure requires a force to install the

rings. Since the rings are not strong in directions perpendicular to the lay of the fibre, the axial length l of each ring is therefore dictated by the maximum axial force allowed during assembly. Referring to Fig. 5, the allowable maximum assembly force F_{max} is limited as follows:

The assembly push load F (in Newtons) for a taper mandrel of included angle α is given by:

$$F = \mu R/\cos(\alpha/2) = \mu \times \pi \times d \times l \times P/\cos(\alpha/2)$$

The compressive assembly stress σ of the retaining ring is given by:

$$\sigma = F/(\pi/4(D^2-d^2))$$

where D is the mean external diameter of the ring; and
d is, as before, the mean internal diameter of the ring.

Since the allowable maximum compressive assembly stress is σ_{max}:

$$\sigma_{max} = F_{max}/(\pi/4(D^2-d^2))$$

$$F_{max} = \sigma_{max} \times \pi/4(D^2-d^2)$$

As shown in the above equations, in order to achieve high interference pressure P, the length l of the retaining ring needs to be reasonably small. If the length l is large and the assembly push load F becomes larger than the allowable maximum assembly force F_{max}, the compressive assembly stress σ of the retaining ring exceeds the allowable maixmum compressive assembly stress σ_{max} and the retaining ring is destroyed. Therefore, it is impossible to apply a single long-length retaining can over the whole axial length of the rotor.

Fig. 6 shows a graph of hoop stress and interference pressure in the carbon fibre ring versus speed in a high speed generator having the above permanent magnet rotor. As shown in Fig. 6, the segments of permanent magnet are

As shown in Fig. 6, the segments of permanent magnet are securely held in place in the normal temperature range of use of the high speed generator. Thus although the interference pressure decreases with increasing rotational speeds, nevertheless it is maintained within acceptable limits up to an operating speed of 50,000 r.p.m.

Because according to the invention it is possible to obtain the required interference fit without using techniques which involve temporarily heating or cooling one component to make the fit possible by thermal differential expansion, the invention enables the segments of permanent magnet to be more surely and easily held in place.

Furthermore, since according to the invention each of the segments of permanent magnet is preferably secured by at least two retaining rings, even if in use one of the rings might be destroyed, the segment of magnet is held by the other ring or rings and cannot move in the radial direction. Therefore, the invention prevents damage caused by contact between the magnets and the stator, and safety is therefore improved.

Furthermore, according to the invention one may select and vary the material of the retaining rings to suit the surrounding temperature of the rotor. For example, if there is in normal use a temperature gradient in the axial direction of the rotor, one may select rings with appropriate heat-resisting properties to tolerate that temperature gradient. Furthermore, one may vary the interference pressures between different retaining rings. Therefore, if the retaining ring which is fitted to the rotor hub at the axial end where the magnet outside diameter is least has the largest interference pressure, this retaining ring may function as a stopper.

CLAIMS

1. A method of assembling a permanent magnet rotor, comprising the steps of:

(a) forming a rotor hub;

(b) holding segments of permanent magnet on the rotor hub;

(c) machining the segments of permanent magnet so that a continuous shallow angle taper is formed over the outer diameter of the segments of permanent magnet from one axial end of the rotor hub to the other axial end; and

(d) axially fitting around the outer circumference of the permanent magnet segments, from the smaller diameter end thereof, a plurality of retaining rings made of high strength composite materials and having a decremental change in inside diameter equivalent to the change in magnet outside diameter due to the effect of the taper, the retaining rings being moved axially to engage the outer circumferential surface of the segments of permanent magnet with a predetermined interference.

2. A method according to claim 1, wherein at least two of the retaining rings are fitted around the outer circumferential surface of each of the segments of permanent magnet.

3. A method according claim 1 or claim 2, wherein the inside diameter of each of the retaining rings has a taper to match that of the outside diameter of the segments of permanent magnet.

4. A method of assembling a permanent magnet rotor, substantially as described herein with reference to the drawings.

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The Patent Office

Application No:	GB 9505933.3	**Examiner:**	Mr J Cockitt
Claims searched:	1-4	**Date of search:**	4 May 1995

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.N): H2A [AKH2, AKF2]; B3A;

Int Cl (Ed.6): H02K [01/27, 01/30]

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
	NONE	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		